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Present status and future tests of the higgsino-singlino sector in the NMSSM

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Abstract: The light higgsino-singlino scenario of the NMSSM allows to combine a naturally small μ parameter with a good dark matter relic density. Given the new constraints on spin-dependent and spin-independent direct detection cross sections in 2016 we study first which regions in the plane of chargino- and LSP-masses below 300 GeV remain viable. Subsequently we investigate the impact of searches for charginos and neutralinos at the LHC, and find that the limits from run I do not rule out any additional region in this plane. Only the HL-LHC at 3000 fb^{-1} will test parts of this plane corresponding to higgsino-like charginos heavier than 150 GeV and relatively light singlinos, but notably the most natural regions with lighter charginos seem to remain unexplored.

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Contents

1 Introduction

Despite considerable efforts the ATLAS and CMS collaborations have not (yet?) discovered supersymmetric particles at the LHC [1, 2]. The most stringent limits are on the masses of squarks and gluinos with strong interactions, but electroweakly interacting supersymmetric particles (charginos $\chi_i^\pm$ and neutralinos χ_i^0) can and have also been searched for.

Among the electroweakly interacting supersymmetric particles are the higgsinos, the fermionic superpartners of the two scalar Higgs doublets H_u and H_d required in supersymmetry (Susy). The higgsinos include a chargino with a Dirac mass μ, and two neutral Majorana fermions which are part of the neutralinos. Charginos have been searched for at LEP, and masses below $\sim 100\,\mathrm{GeV}$ have been ruled out [3, 4] implying a corresponding lower bound on $|\mu|$.

μ is a supersymmetric mass term and generates a positive mass squared term μ^2 in the scalar potential for both SU(2) doublets H_u and H_d, both of which must have non-vanishing vacuum expectation values (vevs) in order to generate up- and down-type quark masses. At least for H_u, the positive mass squared term μ^2 must be cancelled by a negative soft SUSY breaking mass term $m_{H_u}^2$ such that $\mu^2 + m_{H_u}^2 < 0$ leading to $-\mu^2 - m_{H_u}^2 \approx M_Z^2/2$. Such a cancellation becomes unnatural if each of these terms were much larger than M_Z^2, i.e. $\gtrsim (300\mathrm{GeV})^2$. This argument applies both in the MSSM [5–7] (see e.g. [8–11]) and in the NMSSM [12, 13] (see e.g. [14, 15]), where $\mu \equiv \lambda \langle S \rangle$ is generated by the vev $\langle S \rangle$ of a scalar singlet S and λ is a higgsino-S Yukawa coupling.

The lightest neutralino, stable if R-parity is conserved and if it is the lightest supersymmetric particle (LSP), is a candidate for dark matter. Besides the higgsinos, additional neutralinos are neutral electroweak gauginos (bino and the neutral wino) and, in the NMSSM, the singlino, the supersymmetric partner of the scalar S. If one assumes Grand Unification of the gaugino masses lower bounds on the gluino mass M_3 imply also lower bounds on the bino and wino masses M_1 and M_2, respectively. This assumption implies $M_1 : M_2 : M_3 \approx 1 : 2 : 6$ depending somewhat on threshold corrections to the running masses and radiative corrections to pole masses. Then, if $M_3 \gtrsim 2\,\mathrm{TeV}$ (or more) is confirmed in the future, it is natural for the wino and bino masses M_2, M_1 to be larger than the higgsino mass parameter μ.

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In the MSSM, the neutral higgsinos (nearly mass degenerate with the higgsino-like charginos) would then play the rôle of the LSP. However, a nearly pure higgsino LSP is known to be an imperfect candidate for dark matter: unless very heavy with a mass beyond 1 TeV, it annihilates too fast in the early universe implying a too small relic density [16]. (The situation might be remedied introducing additional axions as the dominant component of dark matter in the MSSM [9, 11]. Alternatively, a non-thermal higgsino production in the early universe can be invoked; this scenario is severly constrained by limits from direct dark matter detection experiments [17].)

In the NMSSM it is natural for the singlino to be quite light; the singlino (Majorana) mass parameter $2\kappa \langle S \rangle$ (where κ is a singlino-Singlet Yukawa coupling) might even vanish for $\kappa \to 0$ in which case a small singlino mass results only from mixing with the neutral higgsinos. Still, such a mostly singlino-like LSP is good dark matter candidate [18] since its relic density can be reduced to the observed value via various processes like a mostly singlet-like pseudoscalar in the s-channel, chargino exchange in the t-channel or co-annihilation. Furthermore a mostly singlino-like LSP can easily satisfy limits from direct and indirect dark matter detection experiments; its spin-independent direct detection cross section can even fall below the neutrino floor [19, 20].

It is the purpose of the present paper to investigate in how far this attractive scenario within the NMSSM is tested by the most recent direct dark matter detection experiments PICO-2L [21], LUX [22, 23] and PandaX-II [24, 25], in combination with searches at the LHC for electroweakinos at run I and, in the future, by the high luminosity (HL) LHC.

At the LHC, charginos (higgsino-like or wino-like) can be pair produced, or in association with neutralinos χ_i^0. The lightest chargino can decay via possibly virtual $W^{\pm(*)}$ bosons or, if kinematically possible, via sleptons. The search channels are typically missing transverse energy $E_T^{\rm miss}$ plus two leptons (from leptonic decays of two $W^{\pm}$ bosons in the case of chargino pair production), or three leptons from $pp \to W^{(*)} \to \chi_1^{\pm} + \chi_2^0$ with $\chi_1^{\pm} \to W^{(*)} + \chi_1^0$, $\chi_2^0 \to Z^{(*)} + \chi_1^0$ and leptonic decays of both $W^{(*)}$ and $Z^{(*)}$. This $E_T^{\rm miss}$ + three lepton channel has typically the farthest reach in mass. Another search channel is WH (where H is the Higgs boson of the Standard Model), where one assumes a χ_2^0 decay of the form $\chi_2^0 \to H + \chi_1^0$, still concentrating on the leptonic $W^{(*)}$ decay.

Previous studies of constraints on, phenomenological aspects and future prospects of the light singlino scenario in the NMSSM have been performed in [15, 20, 26–58]. Here we proceed as follows: in the plane defined by the chargino (charged higgsino) mass $M_{\chi_1^{\pm}} <$ 300 GeV and the (mostly singlino-like) LSP mass $M_{\chi_1^0} < M_{\chi_1^{\pm}}$ we look for regions which are or will be definitely excluded by present dark matter searches and/or searches at the LHC. To this end we use the code NMSSMTools_5.0.1 [59, 60] with NMSDECAY [61] to compute the spectrum, couplings and branching fractions, and fix the less relevant soft Susy breaking parameters to quite pessimistic values: the squark masses of the first two generations to 3 TeV, the slepton masses to 1 TeV (disregarding a possible contribution to the muon anomalous magnetic moment), the gaugino masses M_3, M_2 and M_1 to 2.1 TeV, 700 GeV and 350 GeV, respectively, only $A_{\rm top}$ and the stop masses are varied to ensure a Standard Model-like Higgs scalar with a mass of about 125 GeV. The NMSSM specific Yukawa couplings λ and κ, the soft Susy breaking terms A_λ and A_κ, μ and $\tan\beta$ are varied for given points in the $M_{\chi_1^\pm} - M_{\chi_1^0}$ plane. Actually $M_{\chi_1^\pm}$ defines essentially μ, and $M_{\chi_1^0}$ the ratio κ/λ.

The remaining parameters are still varied in order to find the strict boundaries in the above defined plane. These originate from a dark matter relic density consistent with the WMAP/Planck value $\Omega_{DM}h^2 = 0.1187$ [62, 63], allowing for a 10% theory error, and from upper limits on spin-dependent and spin-independent direct detection cross sections from PICO-2L [21], LUX [22, 23] and PandaX-II [24, 25]. The dark matter relic density and the spin-dependent and spin-independent direct detection cross sections are computed with help of micrOMEGAS_3 [64].

In addition various other phenomenological constraints are required to be satisfied. These are notably constraints from LEP on the invisible Z width, from searches for charginos and associate production of neutralinos by DELPHI [65] and OPAL [66], and from searches for MSSM Higgs bosons [67] (which are relevant for a lighter mostly singlet-like scalar). Relevant constraints from the LHC stem from the ATLAS and CMS combinations of Standard Model-like Higgs boson production and decay rates [68], which constrain possible exotic decays into pairs of NMSSM-like scalars, pseudoscalars or singlinos with masses below $\sim 60\,\mathrm{GeV}$. The lower limit on the combined signal rates into the WW/ZZ channels is actually more relevant than the direct searches for exotic decays. All these constraints are implemented in NMSSMTools_5.0.1.

In the next section we describe the model and, in more detail, the constraints from dark matter in the various regions of the $M_{\chi_1^0} - M_{\chi_1^\pm}$ plane. In section 3 we describe our simulations of signals at the LHC, their comparisons with constraints from run I and prospects for the High Luminosity LHC (based essentially on CheckMATE [69–71]). We conclude in section 4 with a summary and outlook.

2 The NMSSM and the singlino relic density

We consider the NMSSM with the scale invariant superpotential

$$W_{\mathrm{NMSSM}} = \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + \dots \tag{2.1}$$

where the dots denote the Yukawa couplings of the superfields $\hat{H}_u$ and $\hat{H}_d$ to the quarks and leptons as in the MSSM. Once the scalar component of the superfield $\hat{S}$ develops a vev $\langle S \rangle \equiv s$, the first term in W_{NMSSM} generates an effective μ-term with

$$\mu_{\mathrm{eff}} = \lambda\, s\ . \tag{2.2}$$

Subsequently the index $_{\mathrm{eff}}$ of μ will be omitted for simplicity. μ generates a Dirac mass term for the charged and neutral SU(2) doublet higgsinos ψ_u and ψ_d. Additional charginos are the charged winos with a mass term M_2. As stated in the introduction we assume $M_2 = 700\,\mathrm{GeV}$ which leads to little mixing $\lesssim 3\%$ between the charged higgsinos and winos.

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Of particular importance will be the neutralino sector. Altogether the symmetric 5×5 mass matrix $\mathcal{M}_0$ in the basis $\psi^0 = (-i\widetilde{B}, -i\widetilde{W}^3, \psi_d^0, \psi_u^0, \psi_S)$ is given by [13]

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa s \end{pmatrix} \tag{2.3}$$

where $v_u^2 + v_d^2 = v^2 \simeq (174\ \mathrm{GeV})^2$ and $\frac{v_u}{v_d} = \tan\beta$. The eigenstates of $\mathcal{M}_0$ are denoted by χ_i^0, $i = 1 \ldots 5$ ordered in mass. Henceforth the LSP is identified with χ_1^0.

Another important rôle will be played by the singlet-like scalar and pseudoscalar Higgs masses. The CP-even sector comprises three physical states which are linear combinations of the real components (H_{dR}, H_{uR}, S_R). The (3,3) element of the 3×3 CP-even mass matrix $\mathcal{M}_S^2$ reads in this basis

$$\mathcal{M}_{S,33}^2 \equiv M_{S_R,S_R}^2 = \lambda A_\lambda \frac{v_u v_d}{s} + \kappa s (A_\kappa + 4\kappa s)\ ; \tag{2.4}$$

it corresponds essentially to the mass squared of the mostly singlet-like eigenstate. Another eigenstate must correspond to a Standard Model-like Higgs boson H_{125} with its mass $\sim$ 125 GeV, and nearly Standard Model-like couplings to quarks, leptons and gauge bosons. A third MSSM-like eigenstate has a mass of about $2\frac{\mu(A_\lambda+\kappa s)}{\sin 2\beta}$. In the regions of the parameter space of interest here we always find that the mostly singlet-like eigenstate is the lightest CP-even scalar H_1, the Standard-Model-like Higgs boson H_{125} is the second lightest CP-even scalar H_2, and the MSSM-like state is the third CP-even scalar H_3.

The CP-odd sector consists in the linear combinations of the imaginary components (H_{dI}, H_{uI}, S_I). The (3,3) element of the 3×3 CP-odd mass matrix $\mathcal{M}_P^2$ reads in this basis

$$\mathcal{M}_{P,33}^2 \equiv M_{S_I,S_I}^2 = \lambda (A_\lambda + 4\kappa s) \frac{v_u v_d}{s} - 3\kappa A_\kappa s\ ; \tag{2.5}$$

again it corresponds essentially to the mass squared of the mostly singlet-like eigenstate. Other eigenstates are the electroweak Goldstone boson, and an MSSM-like eigenstate again with a mass of about $2\frac{\mu(A_\lambda+\kappa s)}{\sin 2\beta}$. The masses of the MSSM-like Higgs bosons are bounded from below to $\gtrsim 300 - 400$ GeV due to constraints from $b \to s\gamma$ on the charged Higgs boson whose mass is similar to the ones of the CP-even and CP-odd neutral scalars. Subsequently the lightest mostly singlet-like CP-odd eigenstate will be denoted by A_1.

From eqs. (2.3)–(2.5) one can derive the sum rule [31]

$$M_{\psi_S,\psi_S}^2 \equiv 4\kappa^2 s^2 = M_{S_R,S_R}^2 + \frac{1}{3} M_{S_I,S_I}^2 - \frac{4}{3} v_u v_d \left(\lambda^2 \frac{A_\lambda}{\mu} + \kappa \right) \tag{2.6}$$

which relates, up to modifications by mixing, the singlet-like neutralino, CP-even and CP-odd Higgs masses. Notably for sizeable $\tan\beta$ (i.e. small v_d) and not too large A_λ and Yukawa couplings λ and κ the last term in eq. (2.6) is negligible.

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In the following we consider, for reasons of naturalness as discussed in the introduction, a μ parameter $\lesssim 300\,\text{GeV}$ - below the bino and wino masses - and hence a dominantly singlino-like LSP χ_1^0 (singlino for short). Assuming a standard thermal history of the universe with a singlino in thermal equilibrium at temperatures above its mass, its annihilation rate must be sufficiently large such that its relic density today complies with the WMAP/Planck value $\Omega_{DM}h^2 = 0.1187$ [62, 63]. Various processes can give a large enough annihilation cross section:

- Annihilation via a pseudoscalar in the s-channel. For singlino masses $M_{\chi_1^0}$ below μ as assumed here this pseudoscalar is the singlet-like A_1 with its mass given in eq. (2.5) (up to a small shift through mixing). For $M_{\chi_1^0}$ below $\approx 100\,\text{GeV}$, M_{A_1} should be about $2 \times M_{\chi_1^0}$ such that the annihilation cross section is enhanced by the s-channel pole (depending on κ and the mixing of A_1 with the MSSM-like SU(2)-doublet pseudoscalar which induces its couplings to quarks and leptons). For $M_{\chi_1^0}$ above $\approx 100\,\text{GeV}$ M_{A_1} can be smaller than $2 \times M_{\chi_1^0}$ allowing for the LSP annihilation via $A_1^* \to A_1 + H_1$ provided M_{H_1} is small enough. For $M_{\chi_1^0}$ above $\approx m_{\text{top}}$ the annihilation via $A_1^* \to t\bar{t}$ becomes possible.
- Annihilation into a pair of W bosons via (higgsino-like) chargino exchange in the t-channel. This t-channel process is strong enough to be dominant only for singlino masses above $\sim\ 100\,\text{GeV}$.
- Annihilation via the Z boson in the s-channel if the singlino mass is about half the Z mass.
- Annihilation via the Standard Model-like Higgs boson H_{125} in the s-channel if the singlino mass is about half the Higgs mass.
- Coannihilation with higgsinos is possible in principle, but strongly limited by the constraints discussed in the introduction and below.

Annihilation via $A_1 \sim S_I$ in the s-channel with a pseudoscalar mass about twice the mass of the singlino is constrained by eq. (2.6): replacing $M^2_{S_I,S_I}$ by $\sim 4M^2_{\psi_S,\psi_S}$ eq. (2.6) becomes

$$\frac{1}{3}M^2_{\psi_S,\psi_S} = -M^2_{S_R,S_R} + \frac{4}{3}v_u v_d \left(\lambda^2 \frac{A_\lambda}{\mu} + \kappa\right) \tag{2.7}$$

leading to a negative CP-even scalar mass squared if the terms $\sim v_u v_d$ are neglected. This conclusion is avoided if one takes into account that the physical masses are obtained through diagonalization of the mass matrices and shifted by mixing. In the cases of the scalars this effect would be contraproductive: for small $M^2_{S_R,S_R}$ below $(125\ \text{GeV})^2$, mixing with the Standard-Model-like or MSSM-like Higgs bosons would decrease the eigenvalue of $\mathcal{M}^2_S$ corresponding to $M^2_{H_1}$ even further. Likewise, mixing in the CP-odd sector among the singlet-like and the heavier MSSM-like states reduces the physical mass of the mostly singlet-like state A_1, aggravating the consequences of the sum rule (2.6) if M_{A_1} is required to be about twice as large as the singlino mass.

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In the neutralino sector, on the other hand, mixing reduces the mass of the singlino and allows it to be about half of the pseudoscalar mass for positive (albeit small) CP-even masses squared. Such mixing requires the term $-\lambda v_u$ in the mass matrix (2.6) to be not too small. Altogether the scenario where annihilation via A_1 with $M_{A_1} \sim 2M_{\chi_1^0}$ leads to a satisfactory relic density is characterized by

— a light singlet-like CP-even scalar H_1,

— a non-negligible higgsino component of the dominantly singlino-like LSP χ_1^0,

— the latter requires a non-negligible value of $\lambda \sim 0.1 - 0.4$ (larger for larger higgsino masses $\sim \mu$ relative to $M_{\chi_1^0}$).

Correspondingly this scenario is subject to the following constraints:

— H_1 must satisfy constraints from Higgs searches at LEP,

— the $BR(H_{125} \to H_1 H_1)$ must remain below $\sim 10\%$ in order not to reduce the Standard Model-like signal rates of H_{125} below its present limits,

— the spin-independent direct detection rate mediated by H_1 in the t-channel must satisfy the ($M_{\chi_1^0}$ dependent) bounds from LUX [23] and PandaX-II [24],

— for $M_{\chi_1^0} + \mu$ below $\sim 200\,\mathrm{GeV}$ limits from DELPHI [65] and OPAL [66] on $Z^* \to \chi_1^0 + \chi_{2,3}^0$ must be satisfied,

— and, of course, the relic density must coincide with the WMAP/Planck value $\Omega_{DM} = 0.1187 \pm 10\%$.

As stated in the introduction, the NMSSM specific Yukawa couplings λ and κ, the soft Susy breaking terms A_λ and A_κ, μ and $\tan\beta$ are varied in order to satisfy all constraints if possible. Still, the combination of these constraints rules out regions in the $M_{\chi_1^0} - M_{\chi_1^\pm}$ plane characterized by $M_{\chi_1^\pm} \sim \mu \lesssim 240\,\mathrm{GeV}$ and $M_{\chi_1^0} \lesssim 100\,\mathrm{GeV}$ (for $M_{\chi_1^0} \gtrsim 100\,\mathrm{GeV}$, annihilation via $A_1^* \to A_1 + H_1$ dominates). These forbidden regions are indicated in blue in figure 1. The dominant constraints inside these blue regions are indicated by "relic density too large or σ_{SI} too large", where σ_{SI} indicates the spin independent direct detection cross section. The limits of LUX and PandaX-II become weaker for smaller $M_{\chi_1^0}$; for $M_{\chi_1^0} \lesssim 10\,\mathrm{GeV}$ the constraints from LEP become dominant, but for $M_{\chi_1^0} \lesssim 5\,\mathrm{GeV}$ all constraints can be satisfied for any value of $M_{\chi_1^\pm}$. Of course, for $M_{\chi_1^0} \sim M_Z/2$ or $M_{\chi_1^0} \sim M_{H_{125}}/2$ annihilation via these bosons in the s-channel is possible, and some of the above constraints are relaxed.

Another forbidden region appears for $M_{\chi_1^0}$ too close to $M_{\chi_1^\pm} \sim \mu \sim M_{\chi_{2,3}^0}$. There mixing between χ_1^0 and the higgsinos $\chi_{2,3}^0$ cannot be avoided, and the higgsino component of χ_1^0 implies a spin-dependent direct detection rate via Z exchange in conflict with constraints from LUX [22] and PandaX-II [25]. (The importance of recent constraints from spin-dependent direct detection experiments on the viable parameter space of the NMSSM has recently been underlined in [58].) Also the relic density tends to be too small if χ_1^0 has a

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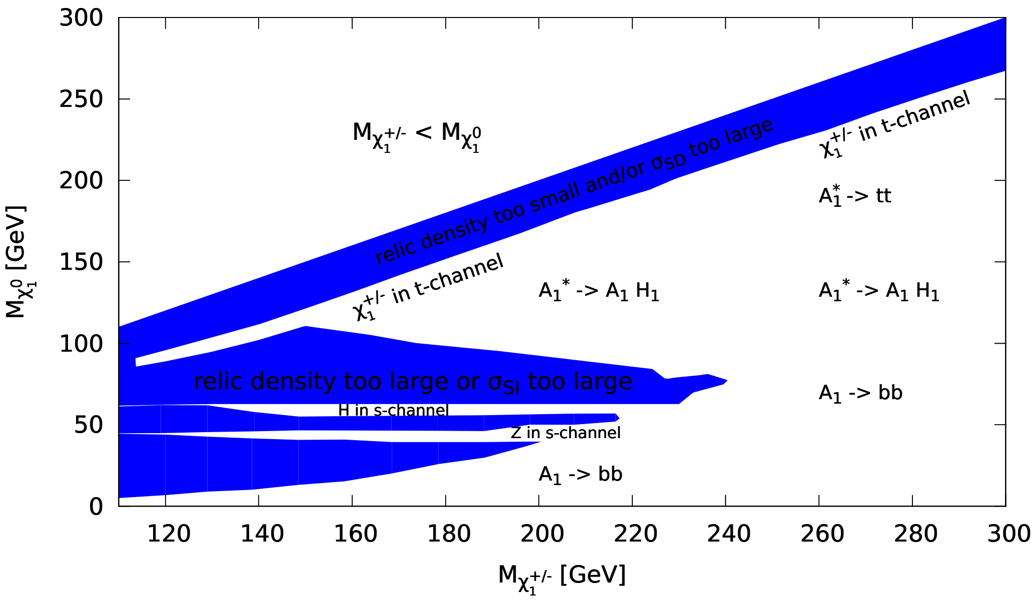

Figure 1. In the blue regions it is impossible to satisfy simultaneously all constraints from a good dark matter relic density, direct dark matter detection cross sections, LEP searches for lighter Higgs bosons and neutralinos, and Higgs signal rates (i.e. the absence of exotic decays) as measured at the LHC. In the viable white regions the dominant processes are indicated which lead to an acceptable relic density.

large higgsino component. This region is indicated by "relic density too small and/or σ_{SI} too large" in figure 1.

In the remaining white (allowed) regions in figure 1 we have indicated the dominant processes which allow for a satisfactory relic density of the singlino-like χ_1^0. Of course, not all parameter values leading to $M_{\chi_1^0}$ and $M_{\chi_1^\pm}$ in the white regions are allowed, but at least one particular choice of parameter values gives a conflict-free good relic density.

Actually, due to the presence of the additional lighter mostly singlet-like Higgs boson H_1 in this scenario, the upper bounds on the spin-independent dark matter cross section mentioned above constrain the parameters everywhere: often the t-channel contribution of H_1 to the scattering amplitude has to be compensated at least partially by a t-channel contribution of H_{125} of opposite sign. Furthermore, for $M_{H_1} \lesssim 60\,\text{GeV}$, the coupling $H_{125} - H_1 - H_1$ must be small enough in order to suppress $H_{125} \to H_1 + H_1$ decays as stated above, and LEP bounds from searches for a light Higgs boson must be respected. These constraints can become relevant all over the white regions.

Additional constraints depend on the dominant processes for the reduction of the relic density:

— $A_1 \to bb$: here M_{A_1} has to be in the range $M_{A_1} \sim 2 \ldots 2.3 \times M_{\chi_1^0}$ for a relic density below the WMAP/Planck value. Of course, fine tuning would be required in order to obtain a relic density within the present $\sim 2\%$ accuracy of the combined WMAP/Planck measurements, but this cannot be blamed to the theory.

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— Z or H_{125} in the s-channel: here $M_{\chi_1^0}$ has to be in the range $M_{\chi_1^0} \sim 39 \ldots 49\,\text{GeV}$ (in the Z case) or $M_{\chi_1^0} \sim 59 \ldots 64\,\text{GeV}$ (in the H_{125} case) for a relic density below the WMAP/Planck value. The couplings of χ_1^0 to Z or H_{125} are proportional to its higgsino component, and hence bounded by the limits on the spin-dependent dark matter cross section. For $M_{\chi_1^\pm} \sim M_{\chi_{2,3}^0} \lesssim (200\text{ GeV} - M_{\chi_1^0})$, constraints from DELPHI [65] and OPAL [66] on $Z^* \to \chi_1^0 + \chi_{2,3}^0$ production require that the higgsino component of χ_1^0 is very small, which implies small couplings to Z and H_{125}. Accordingly $2M_{\chi_1^0}$ has to be very close to the corresponding poles for $M_{\chi_1^\pm} \lesssim 130\,\text{GeV}$.

— $\chi_1^\pm$ in the t-channel: as stated above, here $M_{\chi_1^0}$ is close to $M_{\chi_1^\pm} \sim \mu \sim M_{\chi_{2,3}^0}$ leading to mixing between χ_1^0 and the higgsinos $\chi_{2,3}^0$ inducing potentially a too large spin-dependent direct detection cross section. The reduction of the mixing requires the more tuning the more one approaches the corresponding forbidden blue region.

The satisfaction of all of these constraints requires to tune the dimensionless parameters λ, κ and $\tan\beta$ with a precision of $\sim 1-2\%$ relative to each other nearly everywhere in the white regions, the required tuning of the dimensionful parameters μ, A_λ and A_κ of $\sim 10-30\%$ is weaker. A notable exception is the case of a light χ_1^0 with a mass below $5\,\text{GeV}$ where the present constraints on the dark matter detection cross sections become weak or fade away: the remaining constraints from the relic density and from $Z^* \to \chi_1^0 + \chi_{2,3}^0$ production require only a relative tuning of $\approx 30\%$. However, near the boundaries to the blue regions the parameters have to be tuned more severely in order to satisfy the more and more stringent combinations of constraints (which become impossible to satisfy within the blue regions), hence NMSSM points near these boundaries are necessarily fine tuned.

3 Present and future constraints from the LHC

Searches for charginos and neutralinos at the LHC have been performed by the ATLAS collaboration at run I [72–79] and run II [80–82] and the CMS collaboration at run I [83–90] and run II [91–93]. We recall that the dominant search channels for charginos/neutralinos at the LHC are searches for $2-3$ leptons and E_T^{miss}. The absence of significant excesses in these channels is typically interpreted by the ATLAS and CMS collaborations in terms of simplified models. These mostly assume, however, wino-like charginos $\chi_1^\pm$ (and wino-like neutralinos χ_2^0) which have significantly larger production cross sections than higgsinos.

Specific searches for higgsinos have been performed by ATLAS [72, 76, 78] and CMS [85] assuming a lightest SUSY particle (LSP) in the form of a massless gravitino [85], or the presence of a light stau [76, 78] or light sleptons [78]. Apart from these specific scenarios, light higgsinos are thus hardly constrained by searches at the run I of the LHC, see the analyses within phenomenologically viable versions of the MSSM or NMSSM in [33, 94–109].

The discovery potential for wino-like $\chi_1^\pm/\chi_2^0$ production at the future and high luminosity LHC has been estimated by ATLAS [110, 111] and CMS [112] in the trilepton and WH channels, and seems quite promising at first sight with 95% CL exclusion contours reaching up to a wino mass of about $800\,\text{GeV}$ for a light LSP at $300\,\text{fb}^{-1}$ [110–112].

First we have recast the run I analyses from [73–75, 79] for the light higgsino-singlino scenario of the NMSSM. (The exclusion reach of these analyses in the $M_{\chi_1^0} - M_{\chi_1^\pm}$ plane is not superseeded by others.) As in the previous section we varied the NMSSM parameters for many values of $M_{\chi_1^0}$ and $M_{\chi_1^\pm}$. For the analyses we employed private codes, CheckMATE [69, 70] and CheckMATE 2 [71]. The starting point was always the simulation of events using MadGraph5_aMC@NLO [113]. The output was given to the detector simulation Delphes 3 [114] or analysed directly inside CheckMATE 2 [71].

The result of this recasting was that no region in the $M_{\chi_1^0} - M_{\chi_1^\pm}$ plane is conclusively excluded at the 95% level by the available 3-lepton + E_T^{miss} (and 1-lepton + $H_{125} + E_T^{miss}$) searches at run I, and this not only marginally. The reasons for this result are

— the smaller production cross section for higgsinos compared to winos;

— a further reduction of the higgsino production cross section due to mixing of the neutral higgsinos with the singlino;

— sizeable branching fractions of the neutral higgsinos into the singlino-like LSP + the light singlet-like scalar H_1 (and, less prominently, the light singlet-like pseudoscalar A_1) notably if decays via Z and/or H_{125} are kinematically forbidden. These decays escape detection in the WH final state due to the much smaller singlet-like Higgs mass.

Next we recast the prospects for chargino-neutralino searches at the HL-LHC at $3000\,\text{fb}^{-1}$ into the higgsino-singlino scenario of the NMSSM. The analyses from [110] (which have similar exclusion/detection reaches as the ones in [111, 112]) are implemented in CheckMATE 2 [71].

The relevant signal regions are again the ones dedicated to WZ and WH_{125} final states, with Z or H_{125} originating from $\chi_2^0 \to \chi_1^0 + Z/H_{125}$ decays. Since the search for WZ requires two same-flavour opposite-sign leptons with an invariant mass close to M_Z, it becomes sensitive to the light higgsino-singlino scenario of the NMSSM for $M_{\chi_2^0} \sim M_{\chi_3^0}$ ($\sim M_{\chi_1^\pm}$) $> M_{\chi_1^0} + M_Z$ which is indicated in figure 2 as a black line (below which the inequality is satisfied). Discovery of NMSSM points below this line is thus possible for selected points, since the production cross sections and branching fractions can be large enough for higgsino masses below 300 GeV despite their reduced couplings.

However, even a "3 σ discovery" is not necessarily guaranteed, amongst others for the same reasons as for the run I. Another reason are large cuts on the lepton p_T and E_T^{miss}, which are required to cope with the larger instantaneous luminosity (and the larger background), see the corresponding cuts in [110–112]. So we ask again whether, varying all parameters within the imposed constraints, any region in the $M_{\chi_1^0} - M_{\chi_1^\pm}$ plane can be conclusively excluded at the 95% level at the HL-LHC. The cuts lead to large enough acceptances only for mass differences $M_{\chi_1^\pm} - M_{\chi_1^0} \gtrsim 150 \ldots 200\,\text{GeV}$ (after suffering from the same reductions of the production cross sections and variations of the branching fractions as at the run I). There the decay $\chi_{2,3}^0 \to \chi_1^0 + H_{125}$ becomes also possible with a sufficiently large acceptance.

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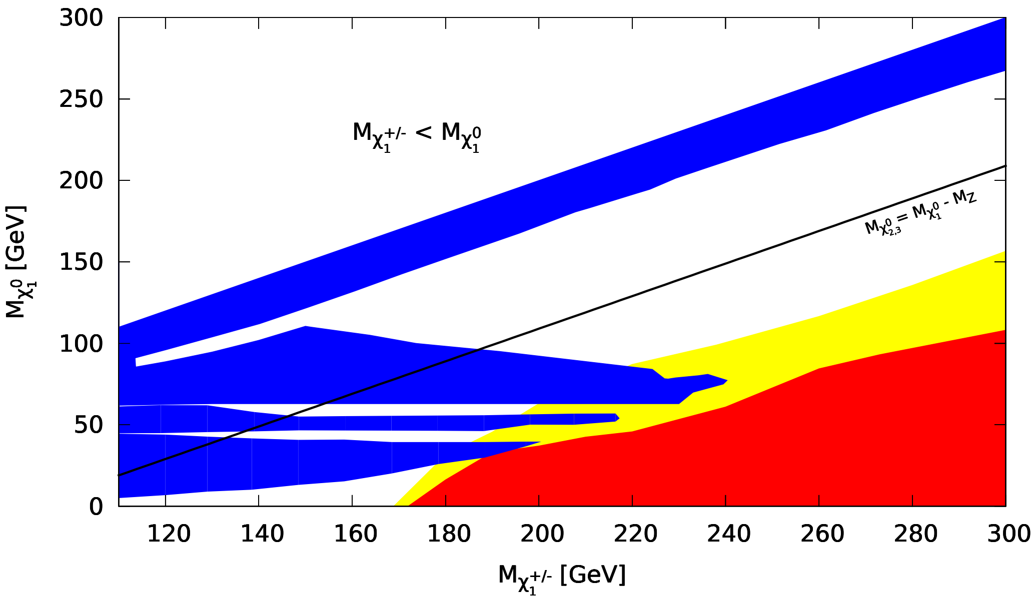

Figure 2. The red region can be excluded at 95% CL at the HL-LHC at 3000 fb^{-1} using a recast of the prospects for chargino-neutralino searches by ATLAS [110]. The yellow region can be excluded according to a search proposed in CheckMATE 2 [71] including hadronic W decays. The blue region is the same as in figure 1.

The region in the $M_{\chi_1^0} - M_{\chi_1^\pm}$ plane which can be excluded at the 95% CL level is shown in red in figure 2. In CheckMATE 2 [71] an additional search region is proposed, which is based on 2 leptons + E_T^{miss} $+W_{had}$, the hadronic decays of W from the $\chi_1^\pm \to \chi_1^0 + W^\pm$ decays. Due to the larger branching fraction of W_{had} this search may cover a slightly larger region in the $M_{\chi_1^0} - M_{\chi_1^\pm}$ plane, which is indicated in yellow in figure 2. The viability of this search channel remains to be confirmed by the experimental collaborations, however. In any case, even the HL-LHC at 3000 fb^{-1} seems unable to test the full $M_{\chi_1^0} - M_{\chi_1^\pm}$ plane in the light higgsino-singlino scenario of the NMSSM.

In figure 2 we have indicated again in blue the regions which are excluded by the combination of constraints notably from the dark matter relic density, and the present constraints from direct dark matter detection. In the absence of signals in the future these latter constraints would become stronger, but we have checked that the boundaries would hardly move. The reason is that the LSP can remain dominantly singlino-like in most regions except for a singlino mass very close to the higgsino (chargino) masses; hence the conclusions would hardly change.

Although one observes a certain complementarity between the constraints from dark matter and the possible future limits at the LHC it is obvious that large regions in the $M_{\chi_1^0} - M_{\chi_1^\pm}$ plane will remain unexplored. This concerns in particular well motivated and natural regions where $M_{\chi_1^\pm} \lesssim 150\,\text{GeV}$ and $M_{\chi_1^0} \lesssim 5\,\text{GeV}$; such light dark matter candidates are difficult to discover via direct detection and the hope was that they are easier to discover at the LHC.

4 Summary and conclusions

The light higgsino-singlino scenario of the NMSSM is probably the most attractive scenario for supersymmetric dark matter, since it allows to combine a small μ parameter with a good relic density and alleviated constraints from dark matter searches. First we have shown that this remains so after the updated constraints on spin-independent and spin-dependent cross sections in 2016. Then we have studied present and future constraints on this scenario from the LHC, and found that even the HL-LHC seems not able to test all possible realizations of this scenario. Possible ways to improve this situation could be:

- To rely on the larger production cross sections of wino-like charginos and neutralinos, and the discovery of lighter higgsinos/singlino via cascade decays. Of course this depends on additional parameters like the wino- (and possibly slepton-) masses and branching fractions. Moreover the transverse momenta of the leptons and E_T^{miss} would again be reduced through multiple cascades.

- To try to become sensitive to smaller transverse momenta of the leptons and E_T^{miss} even at 14 TeV and large instantaneous luminosity by recording and analysing only a fraction of the events.

If such attempts turn out to be fruitless, this attractive scenario could be tested only at an electron-positron collider [115].

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